

ELECTROPHOBIC LORENTZ INVARIANCE VIOLATION FOR NEUTRINOS AND THE SEE-SAW MECHANISM

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In this talk we show how Lorentz invariance violation (LIV) can occur for Majorana neutrinos, without inducing LIV in the charged leptons via radiative corrections. Such “electrophobic” LIV is due to the Majorana nature of the LIV operator together with electric charge conservation. Being free from the strong constraints coming from the charged lepton sector, electrophobic LIV can in principle be as large as current neutrino experiments permit. On the other hand electrophobic LIV could be naturally small if it originates from LIV in some singlet “right-handed neutrino” sector, and is felt in the physical left-handed neutrinos via a see-saw mechanism.

1. Introduction

In this talk we discuss a LIV scenario discussed in ¹ with two desirable features:

- (i) natural explanation of smallness of LIV
- (ii) protection of LIV in the neutrino sector from the bounds coming from the charged lepton sector

We satisfy (i) by supposing that such effects originate in the “right-handed neutrino” singlet sector, and are only fed down to the left-handed neutrino sector via the see-saw mechanism, thereby giving naturally small LIV in the left-handed neutrino sector.

We satisfy (ii) by proposing a LIV operator which violates lepton number by two units - forbidden by electric charge conservation for charged fermions: “electrophobic LIV”

The motivation for LIV in the right-handed neutrino sector is:

- Theoretically attractive since “right-handed neutrinos” could represent any singlet sector, and need not be associated with ordinary quarks and leptons, except via their Yukawa couplings to left-

handed neutrinos.

- The fact that LIV is associated only with such a singlet sector could provide a natural explanation for why LIV appears to be a good symmetry for charged fermions, while being potentially badly broken in the neutrino sector.

2. CPTV in the right-handed neutrino sector

Suppose that CPTV originates solely from the right-handed sector due to the operator:

$$\bar{N}_R^\alpha B'^\mu_{\alpha\beta} \gamma^\mu N_R^\beta \quad (1)$$

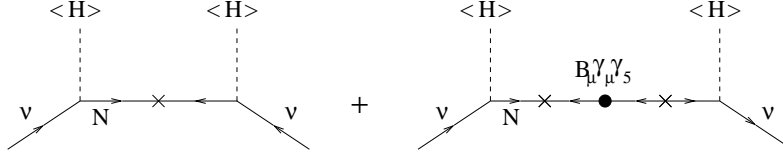


Figure 1. See-saw mechanism with CPT violation in the right-handed neutrino sector.

The see-saw mechanism depicted in Fig.1 leads to a naturally suppressed CPT violating operator in the left-handed neutrino sector: ²

$$\bar{\nu}_L^\alpha b^\mu_{\alpha\beta} \gamma^\mu \nu_L^\beta; \quad b^\mu = \frac{m_{LR}^2 B'^\mu}{(B'^2 + M_{RR}^2)} \quad (2)$$

Mocioiu and Pospelov ² noted the following problem, namely that CPT violation is generated in the *charged* lepton sector via one-loop radiative corrections as shown in Fig.2.

The operator which is generated from Fig.2 is given by:

$$\bar{L}_L^\alpha b_{loop}^\mu_{\alpha\beta} \gamma^\mu L_L^\beta; \quad L_L = (\nu_L \ e_L)^T \quad (3)$$

The CPT violating coefficient from Eq.3 is given by:

$$b_{electron} \sim b_{loop}^\mu \sim 10^{-2} b^\mu \quad (4)$$

The electron CPTV limit in this coefficient is given by: $b_{electron} < 10^{-28}$ GeV which implies that $b < 10^{-26}$ GeV.

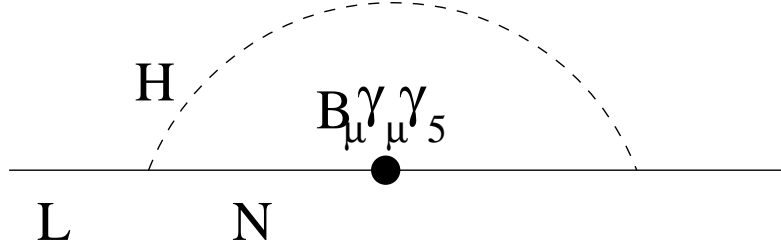


Figure 2. One-loop contribution of CPT violation in the right-handed neutrino sector to CPT violation in the charged lepton sector.

Is such a small amount of CPTV observable in the neutrino sector? To answer this question, consider the constraints arising from the CPTV operator:

$$\bar{\nu}_L^\alpha b_{\alpha\beta}^\mu \gamma_\mu \nu_L^\beta \quad (5)$$

It is conventional to consider the time component only of this operator:

$$\bar{\nu}_L^\alpha b_{\alpha\beta}^0 \gamma_0 \nu_L^\beta \quad (6)$$

The resulting two neutrino flavour equation of motion in the presence of CPTV is:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \left[A \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + B \begin{pmatrix} -\cos 2\theta_b & \sin 2\theta_b \\ \sin 2\theta_b & \cos 2\theta_b \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (7)$$

where

$$A = \frac{\Delta m^2}{4E}, \quad B = \frac{b_2^0 - b_1^0}{2} \quad (8)$$

This results in the oscillation probability that an electron neutrino remains an electron neutrino given by:

$$P_{ee} = 1 - \frac{D^2}{C^2 + D^2} \sin^2 \left(\sqrt{C^2 + D^2} L \right) \quad (9)$$

where

$$C = A \cos 2\theta + B \cos 2\theta_b; \quad D = A \sin 2\theta + B \sin 2\theta_b \quad (10)$$

Neutrino oscillations are sensitive to $b \sim 10^{-20}$ GeV. We therefore conclude that the electron CPTV limit $b_{electron} < 10^{-28}$ GeV above renders any CPT violation in the neutrino sector unobservable.

3. Electrophobic LIV in the Right-Handed Neutrino Sector

In order to overcome this problem we suggested the following LIV operator in the right-handed neutrino sector:¹

$$H'^{\mu\nu}(\overline{N_R^C})_\alpha \sigma_{\mu\nu} (N_R)_\beta; \quad \Delta L = 2 \quad (11)$$

The see-saw mechanism depicted in Fig.3 then leads to naturally sup-

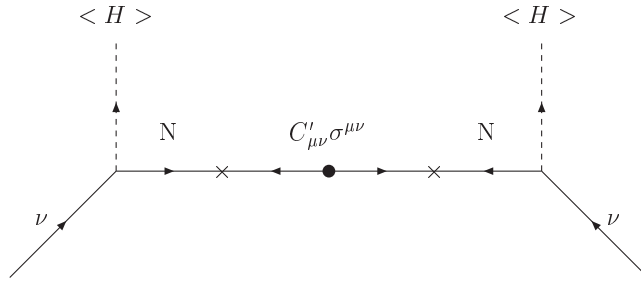


Figure 3. See-saw contribution of LIV operator in the right-handed neutrino sector.

pressed LIV in the left-handed neutrino sector: ^a

$$h_{\alpha\beta}^{\mu\nu}(\overline{\nu_L^C})_\alpha \sigma_{\mu\nu} (\nu_L)_\beta; \quad h^{\mu\nu} = \frac{m_{LR}^2 H'^{\mu\nu}}{(H'^2 + M_{RR}^2)} \quad (12)$$

Note that both operators in Eqs.11,12 are Majorana operators. They can never lead to LIV in the charged lepton sector to all orders of perturbation theory due to electric charge conservation!

Expanding the electrophobic LIV operator in Eq.12:

$$\begin{aligned} h_{\alpha\beta}^{\mu\nu}(\overline{\nu_L^C})_\alpha \sigma_{\mu\nu} (\nu_L)_\beta &= (\nu_{\alpha R}^C)^\dagger \nu_{\beta L} H_+ - (\nu_{\alpha L})^\dagger \nu_{\beta R}^C H_- \\ &\quad + (\nu_{\beta L})^\dagger \nu_{\alpha R}^C H_- - (\nu_{\beta R}^C)^\dagger \nu_{\alpha L} H_+ \end{aligned} \quad (13)$$

where $H_\pm = (h_{23} + h_{01}) \pm i(h_{13} + h_{02})$. Eq.13 shows that electrophobic LIV allows $\nu_\alpha \rightarrow \bar{\nu}_\beta$, whereas the CPT considered previously forbids $\nu_\alpha \rightarrow \bar{\nu}_\alpha$.

^aThis operator is reminiscent of the magnetic moment operator $\mu_{\alpha\beta}(\overline{\nu_L^C})_\alpha \sigma_{\mu\nu} (\nu_L)_\beta F^{\mu\nu}$. The main physical difference is that our operator is independent of any physical magnetic fields, and can in principle be arbitrarily large.

We now consider constraints on the coefficient which controls electrophobic LIV:

$$H_{\pm} \rightarrow h_{23} + h_{01} \equiv H \quad (14)$$

The two neutrino equation of motion is:

$$i \frac{d}{dt} \begin{pmatrix} \nu_{\alpha L} \\ \bar{\nu}_{\alpha R} \\ \nu_{\beta L} \\ \bar{\nu}_{\beta R} \end{pmatrix} = \begin{pmatrix} -A \cos 2\theta & 0 & A \sin 2\theta & B \\ 0 & -A \cos 2\theta & -B & A \sin 2\theta \\ A \sin 2\theta & -B & A \cos 2\theta & 0 \\ B & A \sin 2\theta & 0 & A \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_{\alpha L} \\ \bar{\nu}_{\alpha R} \\ \nu_{\beta L} \\ \bar{\nu}_{\beta R} \end{pmatrix} \quad (15)$$

where

$$A = \frac{\Delta m^2}{4E}, \quad B = H_{\alpha\beta} \quad (16)$$

This leads to the two-flavour oscillation probabilities:

$$P_{\alpha\beta} = \frac{A^2 \sin^2 2\theta}{A^2 + B^2} \sin^2 \left(\sqrt{A^2 + B^2} L \right) \quad (17)$$

$$P_{\alpha\bar{\beta}} = \frac{B^2}{A^2 + B^2} \sin^2 \left(\sqrt{A^2 + B^2} L \right) \quad (18)$$

$$P_{\alpha\alpha} = P_{\bar{\alpha}\bar{\alpha}} = 1 - P_{\alpha\beta} - P_{\alpha\bar{\beta}} \quad (19)$$

$$P_{\alpha\bar{\alpha}} = 0 \quad (20)$$

We now summarise the experimental constraints on electrophobic LIV from different experiments.

Constraints from CHOOZ/Palo Verde:

CHOOZ and Palo Verde short baseline reactor experiments are consistent with no observed oscillation of $\bar{\nu}_e$ at baseline $L \sim 1$ km. This non-observation of any oscillations can be used to constrain $H_{e\bar{\beta}} \lesssim 10^{-19}$ GeV

[$H_{e\bar{\beta}}$ ($= H_{\bar{e}\beta}$ due to CPT invariance) is the LIV coefficient responsible for $\bar{\nu}_e(\nu_e) \rightarrow \nu_{\beta}(\nu_{\bar{\beta}})$ transition.]

Constraints from the KamLAND experiment:

KamLAND observes the electron antineutrinos produced in nuclear reactors from all over Japan and Korea. KamLAND results show a deficit of the antineutrino flux and are consistent with oscillations with Δm^2 and mixing given by LMA solar solution.

KamLAND being a disappearance experiment is insensitive to whether the $\bar{\nu}_e$ oscillate into ν_μ due to mass and mixing or $\bar{\nu}_\mu$ due to LIV. However LIV driven oscillations are inconsistent with the KamLAND energy distortion data leading to $H_{e\bar{\beta}} < 7.2 \times 10^{-22}$ GeV.

Constraints from the atmospheric neutrino data:

The atmospheric neutrino experiments observe a deficit of the ν_μ and $\bar{\nu}_\mu$ type neutrinos, while the observed ν_e and $\bar{\nu}_e$ are almost consistent with the atmospheric flux predictions.

The LIV term would convert $\nu_\mu(\bar{\nu}_\mu)$ into $\bar{\nu}_\tau(\nu_\tau)$, while flavor oscillations convert $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\tau(\bar{\nu}_\tau)$.

Since the experiments are insensitive to either ν_τ or $\bar{\nu}_\tau$, they will be unable to distinguish between the two cases.

LIV case is independent of the neutrino energy (same predicted suppression for the sub-GeV, multi-GeV, and the upward muon data). Therefore pure LIV term fails to explain the data but can exist as subdominant effect along with mass driven flavor oscillations, leading to limit: $H_{\mu\bar{\tau}} \lesssim 10^{-20}$ GeV.

Constraints from the future long baseline experiments: Better constraints on LIV coefficient requires experiments with longer baselines. MINOS and CERN to Gran Sasso (CNGS) experiments, ICARUS and OPERA, have a baseline of about 732 km, though the energy of the ν_μ beam in MINOS will be different from the energy of the CERN ν_μ beam. However, since the LIV driven probability is independent of the neutrino energy, all these experiment would be expected to constrain $H_{\mu\bar{\beta}} \lesssim 10^{-22}$ GeV.

JPARC has shorter baseline of about 300 km only, while the NuMI off-axis experiment is expected to have a baseline not very different from that in MINOS and CNGS experiments. The best constraints in terrestrial experiments would come from the proposed neutrino factory experiments, using very high intensity neutrino beams propagating over very large distances. Severe constraints, up to $H_{\mu\bar{\beta}} \lesssim 10^{-23}$ GeV could be imposed for baselines of $\sim 10,000$ km.

Constraints from solar neutrinos:

Neutrinos coming from the sun, travel over very long baselines $\sim 1.5 \times 10^8$ km. So one could put stringent constraints on $H_{e\bar{\beta}}$ from the solar neutrino data. However the situation for solar neutrinos is complicated due to the presence of large matter effects in the sun.

Constraints from supernova neutrinos:

Supernova are one of the largest source of astrophysical neutrinos, re-

leasing about 3×10^{53} ergs of energy in neutrinos. The neutrinos observed from SN1987A, in the Large Magellanic Cloud, had traveled ~ 50 kpc to reach the earth. Neutrinos from a supernova in our own galactic center would travel distances ~ 10 kpc. These would produce large number of events in the terrestrial detectors like the Super-Kamiokande. The observed flux and the energy distribution of the signal can then be used to constrain the LIV coefficient.

Constraints using the time of flight delay technique:

The violation of Lorentz invariance could also change the speed of the neutrinos and hence cause delay in their time of flight. The idea is to find the dispersion relation for the neutrinos in the presence of LIV and extract their velocity $v = \partial E / \partial p$, where E is the energy and p the momentum of the neutrino beam. Then by comparing the time of flight of the LIV neutrinos, with particles conserving Lorentz invariance, one could *in principle* constrain the LIV coefficient. The presence of the LIV term in the Lagrangian gives a see-saw suppressed correction to the mass term. Therefore

$$v \approx 1 - \frac{m^2 + m_{LIV}^2}{E^2}$$

where m is the usual mass of the neutrino concerned and m_{LIV}^2 is the LIV correction.

4. Conclusion

- LIV may be introduced into a “right-handed neutrino” sector at some high scale, resulting in suppressed LIV in the left-handed neutrino sector via the see-saw mechanism.
- The $\Delta L = 2$ lepton number violating operators induce LIV into the left-handed Majorana neutrino sector, while protecting LIV in the charged lepton sector to all orders of perturbation theory due to electric charge conservation

References

1. S. Choubey and S. F. King, Phys. Lett. B **586** (2004) 353 [arXiv:hep-ph/0311326].
2. I. Mocioiu and M. Pospelov, Phys. Lett. B **534** (2002) 114 [arXiv:hep-ph/0202160].